Correlation between Cu precipitates and irradiation defects in Fe-Cu model alloys investigated by Positron annihilation spectroscopy

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Abstract

The correlation between Cu precipitates and vacancy-like defects in three Fe-Cu model alloys, Fe-0.15%Cu, Fe-0.3%Cu and Fe-0.6%Cu, irradiated at 400 °C with hydrogen ions at doses from 0.045 to 0.45 dpa, were revealed by positron annihilation spectroscopy. The formation of vacancy-like defects surrounded by tiny Cu precipitates induced the increment of the S and W parameters after irradiation. The peak value of the relative W parameter (ΔW/W), as the high momentum information on Cu precipitates, located in the track region and decreased with irradiation dose increased from 0.045 dpa to 0.45 dpa. The information on high momentum depended on the coverage fraction of the defects by Cu atoms. The effect of the irradiation dose, the irradiation depth and the Cu content on the Cu coverage fraction of the defects has been investigated in the present work.

Keywords: Fe-Cu model alloy; Hydrogen ion-irradiation; Cu precipitate; defect; Positron annihilation

1. Introduction

Irradiation-induced defects and Cu enriched precipitates are the major contributors to the increase in hardness and embrittlement in nuclear reactor pressure vessels (RPV) steels. However, the RPV steels contain many minor elements, for instance the SA508Gr3 [1] and A508-3 steel [2]. For the sake of avoiding the effect of foreign atoms with low concentration, Fe-Cu binary alloy was chosen in present work. The Fe-Cu alloy system has been regarded as one of the most suitable systems for studying the formation Cu precipitates and defect evolution.

Ion irradiation experiments have been employed to simulate the radiations produced in nuclear reactors due to without nuclear radioactive pollution for post-irradiated samples and the reduction of the irradiation time for the same irradiation dose. Hydrogen ion is just one nucleon, which is the most similar with

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neutron. It is considered to be one of the most suitable ion sources [3]. In order to clarify the effect of irradiation defects on the formation of Cu precipitates, it becomes very important to study the interaction between irradiation induced defects and Cu atoms. While solute hydrogen atom interacts with vacancy defect, hydrogen could enhance the vacancy activities in materials. The hydrogen ions (H_n), as the impurity atoms, would occupy the vacancy-like defect and form the superabundant vacancy (H_nV_m or/and H_n-void complexes), which has been observed by the x-ray analysis in previous report [4]. The activation energy of a hydrogen atom migration in pure Fe is 0.059 eV [5]. According to the effective-medium theory calculations, the hydrogen trapping energies for the formation of HV and H_2V are ~0.8 eV, while that of H_3V-H_6V formation are between the 0.45eV and 0.55 eV [6]. Thus, the de-trapping energy of the hydrogen atoms from the α-Fe needs more than 0.859 eV, which means that hydrogen atoms could easily escape from vacancy-like defects at elevated temperature. Ishizaki et al. suggested that the hydrogen atoms would not influence the vacancy defect evolution in hydrogen ion irradiated Fe after 350 °C annealing for 1 h [5]. In order to exclude the interference of hydrogen atom on the Cu precipitate, three types of Fe-x%Cu alloys (x= 0.15, 0.3, and 0.6) was irradiated with hydrogen ions at 400 °C. Elevating temperature irradiation was desorption of the hydrogen atoms from vacancy-like defects, and avoid the influence of the H_nV_m complexes on the leaving vacancy-like defects. The main purpose of the present study is to investigate correlation between Cu precipitates and vacancy-like defects in Fe-Cu model alloy, and we also investigate the dependence of Cu precipitation on the irradiation depth and Cu content.

As well known, the positron is a self-seeking probe for vacancy-like defects in condensed matter [7], which would exclusively annihilate with the defect surrounding electrons and two gamma rays are emitted. In Doppler broadening (DB) spectra of positron annihilation, the S parameter is defined as gamma rays with a small energy displacement from the peak centre because of positron annihilation with low-momentum valence electrons; while the W parameter is gamma rays with a large energy shift from the peak centre due to positron annihilation with high-momentum regions of inner shell electrons. It is thus the not only DB spectra measurement that can provide information about vacancy-like defects produced under irradiation, to a certain, but also detect their chemical environment and convey information on Cu element precipitates in Fe-Cu alloys [8]. Recently, coincidence Doppler broadening (CDB) which is improved by using a two-Ge-detector system is able to identify the impurity atoms definitely around the annihilation sites by decreasing the background of high momentum contributions [9].

In this work, we employ DB and CDB technology based on a slow positron beam to measure the vacancy-like defect and nanosize Cu precipitates in three types of Fe-x%Cu alloys (x= 0.15, 0.3, and 0.6) irradiated with hydrogen ions at 400 °C.

2. Experimental Procedures

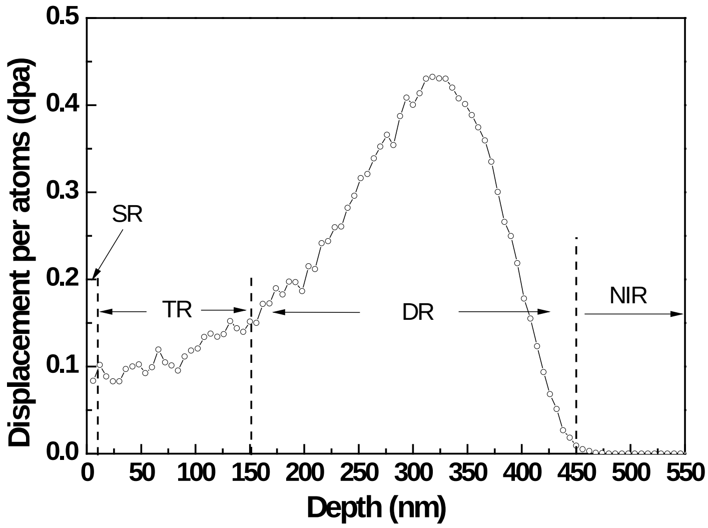

Fig. 1. Dependence of damage profiles produced by 70 keV hydrogen ions on the ion implantation depth. SR is the surface region. DR is the Damage region, corresponding to the region where incident hydrogen ions mainly interact with alloy atom via nuclear collisions. TR denotes the tracks region located between the SR and DR, and corresponding to the zone where ions slow down mainly by electronic energy loss processes. NIR denotes the non-implanted region.

As the starting materials, three types of Fe-x%Cu alloys (x= 0.15, 0.3, and 0.6, in weight percent) were prepared from Fe (99.995% purity) and Cu (99.999% purity) in vacuum using a high-frequency induction furnace. After melting, the solution treatment of alloys was carried out at 800 °C for 24 h followed by quenching in ice water. The bulk materials were rolled to a thickness of 0.5 mm and then cut into 10 mm × 10 mm square sheets. Well-annealing were carried out at 900 °C for 2 h in vacuum, and then the samples were quenched in ice water. Hydrogen ion irradiation was carried out at 400 °C using an ion implanter located in the Accelerator Laboratory of Wuhan University after electrochemical polishing and cleaning. The energy of the hydrogen ion was 70 keV and the irradiation fluences were 1×10^{16} ions/cm^2 and 1×10^{17} ions/cm^2, corresponding to a maximum damage dose of 0.045 dpa and 0.45 dpa, respectively. The damage profiles calculated by SRIM 2008 are shown in Fig. 1, where the displacement energy was 40 eV.

Positron annihilation DB and CDB measurement were carried out at slow positron beam facility in Institute High Energy Physics. Slow positrons are generated by a 1.85 GBq ^{22}Na radiation source and the positron beam energy range is from 0.18 to 20 keV. The detective depth of the slow positron is defined by the incident energy and is calculated by the empirical equation [10, 11].

$$Z(E) = \left(\frac{4\times10^4}{\rho}\right)E^{1.6}, \tag{1}$$

where Z(E) is the depth below surface and is expressed in nm, E is the incident energy (keV) of the slow positron, and ρ is the pure Fe density in units of kg/m^3. The

calculated mean depth below the surface of the slow positron is shown in the top x-axis of Fig. 2 according to Eq. (1). At present, we mainly studied the defects in the track region (TR), damage region (DR) and neglected surface region (SR) because of the influence of surface effect on positron (0.18 – 1 keV, ~5 nm). The TR and DR were about from ~5 nm to ~150 nm and from ~ 150 nm to ~ 450 nm, respectively, shown in Fig. 1. The S and W parameters are defined as the ratios of the counts in central low momentum area (510.2 - 511.8 keV) and two flanks high momentum regions (514.83 - 518.66 keV and 503.34 - 507.17 keV) in the DB spectra to the total counts, respectively. The S parameter represents information on positron annihilation with vacancy-like defects and the W parameter conveys information on Cu element precipitates. CDB spectra were carried out to measure the not irradiated pure Fe, Cu 0.045 dpa and 0.45 dpa irradiated Fe-0.3%Cu alloys using two-Ge-detectors, which decreased the background of high momentum contributions and was useful in studying the Cu element variation around the defect site [12].

3. Results and discussion

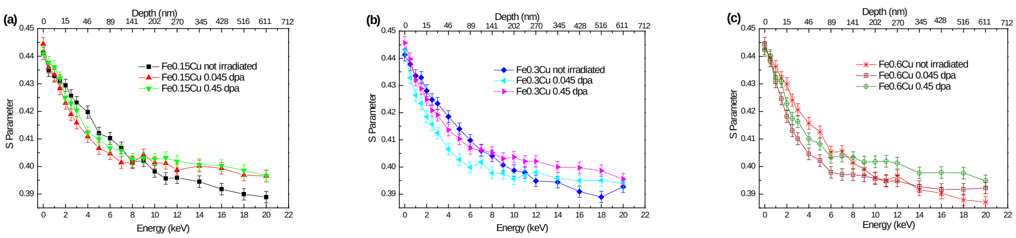

Fig. 2. S-E curves for Fe-0.15%Cu, Fe-0.3%Cu and Fe-0.6%Cu irradiated with different dose

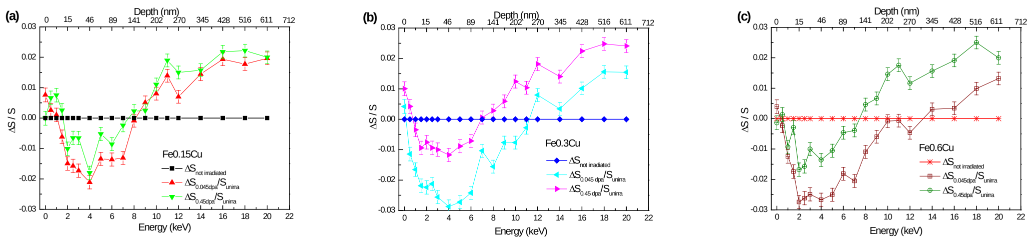

Fig. 3. ΔS/S as a function of the positron energy (depth) in Fe-0.15%Cu and Fe-0.3%Cu and Fe-0.6%Cu

The S parameter-as function of incident positron energy (S-E curves) dependent on different hydrogen ion irradiation doses for three types of Fe-x%Cu alloys (x= 0.15, 0.3, and 0.6) studied is shown in Fig. 2. For the not irradiated samples, only vacancies were introduced by quenching [13, 14], and the S parameters was also added in Fig. 2. In Fig. 2a, the S values for irradiated specimens in damage region (the positron energy is from 8 keV to 20 keV) was larger than that of the not irradiated. The S parameter for Fe-0.15%Cu alloy irradiated to 0.45 dpa was slightly larger than that of 0.045 dpa irradiated one. The similar phenomena also existed in Fe-0.3%Cu (Fig. 2b) and Fe-0.6%Cu alloy (Fig. 2c). The increasing of S parameter corresponded to the growth of vacancy-like defects in Fe-Cu model alloys irradiated with fission neutrons [15], Thus, the results indicated that hydrogen ion irradiation produced a lot

of vacancy-like defects in the DR and higher irradiation dose produced more vacancy-like defects at elevated temperature. In our previous studies, at room temperature, the 1.0 dpa hydrogen ion irradiation produced vacancy-like defects was not larger than that produced by 0.1 dpa irradiation. Hydrogen atoms (H_n) would occupy vacancies (V_m) and form the V_mH_n complexes at room temperature which can affect the annihilation of positrons with the electrons in vacancy-like defects [16]. But the vacancy behavior is not influenced by hydrogen atoms at above 350 °C, because these could easily escape from vacancies [5]. It preliminary indicated that elevated temperature irradiation could suppress the formation of the V_mH_n complexes. However, the S values for all specimens irradiated at 400 °C in Fig. 2 decreased with increasing positron energy, and no expected peaks in the S parameters appeared according to the SRIM calculation (see Fig. 1). The relative S parameter (ΔS/S) was denoted by the following formulation, which could be more accurate to represent the concentration of vacancy-like defects induced by hydrogen ion irradiation.

$$\Delta S/S = \frac{(S_{\text{irradiated}} - S_{\text{not irradiated}})}{S_{\text{not irradiated}}} \tag{2}$$

Fig. 3 indicates that the dependence of ΔS/S parameters on the positron energy (depth) in three types of Fe-x%Cu alloys (x= 0.15, 0.3, and 0.6) irradiated with the dose of 0.045 dpa and 0.45dpa, which reveals two dramatic phenomena. First of all, in the DR of Fig. 3, the maximum value of ΔS/S parameter reached at the depth ~ 500 nm, which was larger than the damage peak depth (~ 320 nm) in Fig. 1. It is well known that vacancies in Fe are mobile well below room temperature [7, 17]. The vacancies introduced by hydrogen ion irradiation around 400 °C can easily migrate and diffuse during irradiation, and hence the vacancy-like defects were likely to diffuse to the more depth region. Secondly, the values of ΔS/S parameter were negative from 1 keV to 8 keV and the valley appeared in the TR of irradiated samples, and the lowest value of the valley located at ~ 4 keV (~ 50 nm) for the three types of Fe-x%Cu alloys. This is also an unexpected phenomenon, which originated from the following two facts: (i) the positron diffusion length for the irradiated specimen is different from that for not irradiated one; (ii) the formation of copper precipitates is due to aggregations of vacancies and Cu atoms. In the range of 2 keV–8 keV, the S parameters of unirradiated specimens were higher than the intrinsic values due to the effect of the surface region [18]. Thus, the positron diffusion length was reduced by irradiation-induced vacancy-like defects and copper precipitates. As a result, the S parameters of the irradiated specimens became close to the intrinsic value even in the same energy range, and they would became relatively smaller. The vacancies introduced by the irradiation at elevated temperature can easily migrate during irradiation, and hence some of them encountered Cu impurity atoms [19]. Cu atoms, just like the impurity atoms [20, 21], could occupy the vacancies, and the Cu-vacancy complexes formed [22, 23]. The Cu-vacancy complexes would enhance the increment of W parameters. It is also clear that the changes of S and W are not independent, and S and W values are in a non-rigorous inverse relationship in generally. Thus, the increment of W parameters will decrease partially the S value in irradiated specimens. What’s more, the elevated temperature could enhance the dissociation of vacancies

from the Cu-vacancy clusters and tend to the formation of the defect-free Cu precipitates [19, 24].

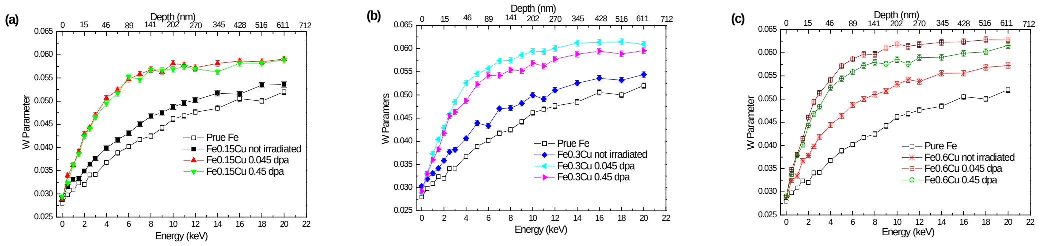

Fig. 4. W-E curves for Fe-0.15%Cu, Fe-0.3%Cu and Fe-0.6%Cu irradiated with different dose

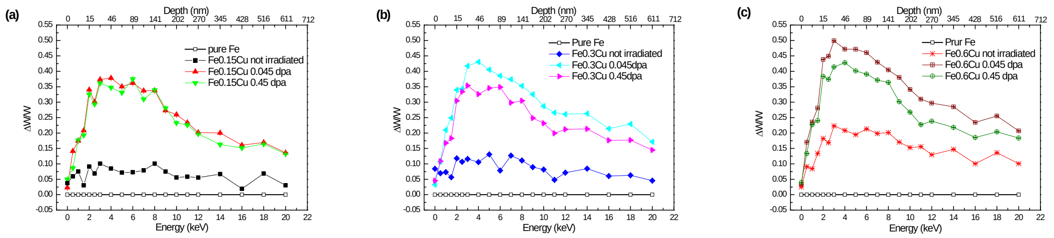

Fig. 5. ΔW/W as a function of the positron energy (depth) in Fe-0.15%Cu, Fe-0.3%Cu and Fe-0.6%Cu. Pure Fe was measured as reference.

Fig. 4 shows the W-E (W parameter-positron energy) curves for Fe-0.15%Cu, Fe-0.3%Cu and Fe-0.6%Cu alloys irradiated with different dose, and the W-E curve of un-irradiated pure Fe sample also plots for comparison. The W parameter exhibits the information on high momentum regions, which is the positron annihilation with their core electrons specific to the Cu and Fe elements. Compared to the pure Fe, all the W parameter in not irradiated Fe-Cu alloys increased, as shown in Fig. 4. Only Cu element was addition in alloys. The increment of the W parameters can be attributed to the annihilation of positrons and 3d electrons of Cu atoms, which is used to estimate the density of Cu atoms around positrons when they are annihilated. With the irradiation dose increased to 0.045 dpa, W increased while no obvious distinction in W was from 0.045 dpa to 0.45 dpa in Fig. 4a. For the W results of Fe-0.3%Cu and Fe-0.6%Cu in Figs. 4b and 5c, contrary they decreased from 0.045 dpa to 0.45 dpa. With the purpose of enlarging the W data proportional relation and studying the Cu precipitates increment in Fe-Cu alloys, the relative W parameter (ΔW/W), analogy to the ΔS/S, was denoted by the following formulation (3):

$$\Delta W/W = \frac{(W_{\text{irradiated}} - W_{\text{pure Fe}})}{W_{\text{pure Fe}}} \tag{3}$$

Where $W_{\text{pure Fe}}$ is the W parameter of pure Fe, which is as the reference. According to the equation (3), ΔW/W parameters as a function of the depth in Fe-0.15%Cu, Fe-0.3%Cu and Fe-0.6%Cu alloys are shown in Fig. 5. Compared to the pure Fe and not irradiated Fe-Cu alloys, ΔW/W parameters increased for the irradiated specimens. However, the ΔW/W parameters for 0.045 dpa irradiated Fe-0.3%Cu and Fe-0.6%Cu alloys were larger than the values for higher dose (0.45 dpa), and the ΔW/W parameters for higher dose irradiated Fe-0.15%Cu was not larger than that for lower

dose. The similar experimental phenomena was also reported in the literatures [25, 26]. In the literature [25], Fe-0.3%Cu and Fe-0.6% were irradiated with 2.5 MeV Fe ion at 573 K to the dose of 0.1 dpa and 1.2 dpa in which the CDB spectrum intensity of Cu peak is higher with 0.1 dpa dose than 1.2 dpa. For the neutron irradiated Fe-0.1%Cu and Fe-0.3%Cu alloys, the CDB ratio data of the high momentum region ($P_L > 7\times10^{-3}$ m_0c) gradually decreased with the increasing irradiation dose [26]. As we discussed above, Cu-vacancy complexes formed during irradiation. The high binding energy between a Cu and a vacancy would promote the aggregation of Cu-vacancy complexes with each other due to a size effect or to the high clustering tendency in the Fe-Cu system [27]. An agglomerate of ~ ten Cu-vacancy complexes was stabilized eventually due to aggregation with each other [19]. The vacancy-like defect induced by irradiation could facilitate the Cu atoms aggregation, and the strong Cu atoms could substitute Fe atoms in the first shell surrounding the vacancy-like defect because of the fact that Cu has a lower surface energy than Fe [28]. With the Cu precipitates grew larger, they released the coherency strain energy due to the transformations such as bcc to 9R structure, which would also induce the vacancy-like defects within the Cu precipitates [7]. The high momentum distribution in CDB spectra or W parameters was proportional to the coverage fraction of the vacancy-like defect by Cu atoms (i.e. the fraction of Cu atoms that substituted Fe in the first shell surrounding the annihilation site). The estimated fraction of Cu atoms in the inner surfaces of the defect would decrease with the increasing of irradiation dose [26]. For the lower dose (0.045 dpa) irradiated Fe-Cu alloys, a lot of tiny Cu precipitates with vacancy-like defects were produced, and positrons could be trapped easily by these vacancy-like defects surrounded by Cu atoms [19, 29]. But in 0.45 dpa irradiated specimens, vacancies are formed to clusters and complex clusters [25], and the size of the vacancy-like defect increased. It would decrease the coverage fraction of the defects by Cu atoms. It could lead to the increasing of S parameters and decreasing of Cu peaks. Thus, the decrease of the $\Delta W/W$ parameters for higher dose irradiated samples was due to the size increment of vacancy-like defects, which could reduce the annihilations with the core electrons by the trapping at the vacancy-like defect surrounded by Cu atoms. Mostly noticeably all, the peaks for $\Delta W/W$ parameters in Fe-0.15%Cu, Fe-0.3%Cu and Fe-0.6%Cu alloys were appeared at 4 keV nearby, and peaks were not at predicted damage region (higher dose region). According to the results of SRIM in Fig. 1, the irradiation dose in TR was smaller than that in the DR. The coverage fraction of the defects by copper atoms in TR was larger than that in DR. Thus, the high momentum distribution was larger in TR, which also decreases the $\Delta S/S$ parameters, as shown in Fig. 3. Xu et al. reported that the growth of Cu precipitates depended on the nucleation and growth of vacancy-like defects, which did not increase monotonically with increasing irradiation dose [30]. Therefore, the growth of irradiation defects increased with the increasing irradiation dose, while the Cu precipitate does not monotonously depend on the dose in present study.

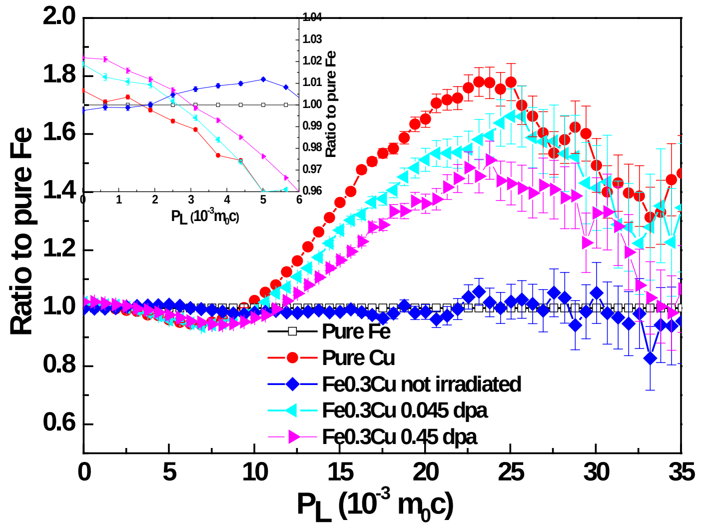

Fig. 6. Ratio curves of the CDB spectra, including pure Cu, Fe-0.3%Cu alloy irradiated with 0 dpa 0.045 dpa and 0.45 dpa with respect to that of pure Fe. Inset: the detailed information as the momentum lower than 6 (10^{-3} m_0c).

Fig. 6 shows the CDB ratio curves for Fe-0.3%Cu alloys as quenched (not irradiated), 0.045 dpa and 0.45 dpa irradiated samples. For comparison and illustration, the ratio curve for pure Cu normalized to pure Fe is also reported. A broad peak around 25 × 10^{-3} m_oc and a small valley at 7 × 10^{-3} m_oc appeared in the ratio curve of pure Cu, which represented Cu characteristic features. The ratio curve of the as-quenched Fe-0.3%Cu alloy was constant at the value of 1, which was similar with the pure Fe curve. It suggested that the positron annihilated only with the Fe electrons. However, the ratio curves for the 0.045 dpa and 0.45 dpa irradiated Fe-0.3%Cu alloys were very similar to that for pure Cu except for the small amplitude, having the Cu characteristic peak and valley. It can be attributed to that the positrons are trapped at vacancy-like defects bound to Cu atoms or confined in Cu precipitates [19]. All the irradiated Fe-0.3%Cu alloys have enhancement in the low momentum region (< 6 × 10^{-3} m_oc) as shown in the inset of Fig. 6, which indicates that positrons are trapped and annihilated in the defects induced by irradiation such as vacancies and voids [24]. Therefore, a lot of tiny Cu precipitates bound to the vacancy-like defects and/or Cu precipitates in matrix were formed easily at 0.045dpa. As increasing the irradiated dose from 0.045 dpa to 0.45 dpa, the amplitude/peak decreased, which was consistent with the results of W and ΔW/W parameters as shown in Figs. 4b and 5b. The size increasing of the vacancy-like defects induced by higher dose irradiation could decrease the coverage of the defects by Cu atoms.

The ratio curves of the CDB spectra of pure Fe, not irradiated, 0.045 dpa and 0.45 dpa Fe-0.3%Cu alloys to that of pure Cu are also shown in Fig. 7. The ratio curve for not irradiated sample was very similar with that of pure Fe (i.e., both the curves have valley at ~ 25 × 10^{-3} m_oc). However, it is noteworthy that the curves for 0.045 dpa and 0.45 dpa irradiated samples were quite different, and they were almost flat in high momentum (> 15 × 10^{-3} m_oc) region. It indicated that the positron don’t

annihilated with electrons in Fe after irradiation [7, 15]. Therefore, the trapping positron vacancy-like defects induced irradiation was not in the matrix, which was bound to the Cu precipitates.

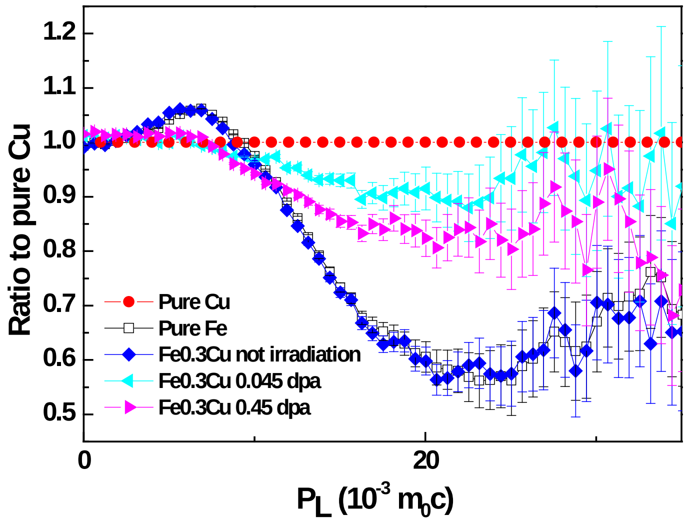

Fig. 7. Ratio curves of the CDB spectra, including pure Fe, Fe-0.3%Cu alloy irradiated with 0 dpa, 0.045 dpa and 0.45 dpa with respect to that of pure Cu.

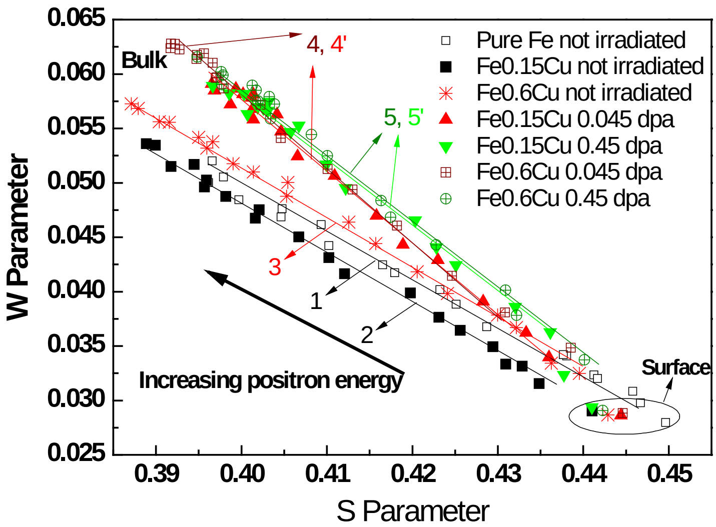

Fig. 8. S versus W plots for the Fe-0.15%Cu and Fe-0.6%Cu irradiated with different dose, and the S-W curve of not irradiated pure Fe also included. The arrow indicates the increasing positron implantation energy.

The correlation between Cu precipitation formation and irradiation induced defects is represented by the S-W plots, as shown in Fig. 8. The plots of the lower Cu content alloy (Fe-0.15%Cu) and the curves for the higher Cu alloy (Fe-0.6%Cu) were compared together. The gradient values for pure Fe, not irradiated Fe-0.15%Cu and Fe-0.6%Cu alloys (lines 1, 2 and 3) were almost the same. The slopes for the 0.045 dpa irradiated Fe-0.15%Cu and Fe-0.6% (lines 4 and 4′) are slightly larger than that of

the higher dose (0.45 dpa) irradiated Fe-Cu alloys (lines 5 and 5′). The slopes of lines 5 and 5′ are larger than that of not irradiated Fe-Cu alloys. As the irradiation dose increased from 0.045 dpa to 0.45 dpa, the slopes decreased, which were consistent with the W parameter and CDB results. The increment of the gradient values compared to the not irradiated Fe-Cu alloys was due the Cu precipitates formation. It is worth noting that all the (S, W) points (except for the surface points marked by ellipse) were almost at the same linear function from the surface region to bulk region along the increasing positron implantation energy, as indicated by the arrow. The slope of the S-W plot could represent mechanism of positron annihilation after trapped, and the S-W plot could be used to identify the number of defect types which are trapped by positrons in materials [10, 25]. These say that only one type defect were detected in irradiated Fe-Cu alloys by the positrons. The formation of Cu characteristic peak and valley in CDB (Fig. 6) for the irradiated Fe-Cu alloys was due to the positrons are annihilated with Cu core electrons in Cu-vacancy complexes or Cu precipitates in matrix. The positron affinity of Cu is ~1 eV higher than that of Fe [7], and the affinity of Cu precipitates is lower than that of vacancy-like defects [15]. Therefore, only the vacancy-like defect surrounded by Cu atoms formed in irradiated Fe-Cu alloys because of the aggregation of Cu-vacancy complexes.

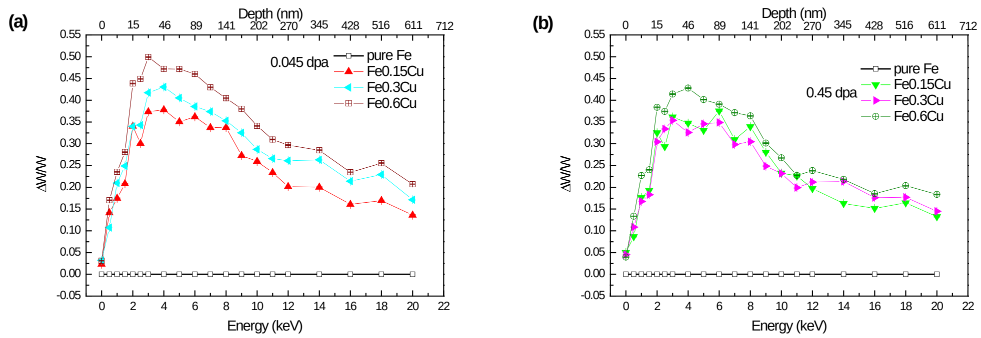

Fig. 9. Dependence of ΔW/W on the positron energy (depth) and Cu content in Fe-Cu alloys irradiated with the dose of 0.045 dpa (a) and 0.45dpa (b).

Fig. 9 shows the dependence of ΔW/W parameters on Cu content in Fe-Cu alloys irradiated with the dose of 0.045 dpa and 0.45 dpa. The ΔW/W parameter increased with the increasing of Cu content. The Cu content increasing in Fe-Cu alloys would enhance the coverage of the defects by copper atoms [26]. Compared Fig. 9a with Fig. 9b, the change of Cu peaks with Cu content in 0.45 dpa specimens is few (Fig. 9b), but it is increased with Cu content in 0.045 dpa specimens as shown in Fig. 9a. This could also attribute to a lot of tiny Cu precipitates with vacancy-like defects were produced at 0.045 dpa, and the formation of clusters and complex clusters would decrease the coverage with copper on the surfaces of the defects at 0.45 dpa.

4. Conclusion

Three Fe-Cu model alloys, Fe-0.15%Cu, Fe-0.3%Cu and Fe-0.6%Cu, were irradiated with hydrogen ions at doses from 0.045 dpa to 0.45 dpa at 400 °C to investigate the correlation between Cu precipitates and irradiation defects. It is found that the increment of S and W parameters after irradiation was due to the formation of

the vacancy-like defects and Cu precipitates. By analyzing the effect of the irradiation dose on DB, CDB and S-W results, only the vacancy-like defect surrounded by Cu atoms was detected by positrons in irradiated Fe-Cu alloys because of the aggregation of Cu-vacancy complexes. With the irradiation dose increased from 0.045 dpa to 0.45 dpa, the $\Delta W/W$ parameter, the Cu characteristic peak in CDB spectra and the slope of the S-W curve decreased. The decrease of higher dose irradiated samples was due to the size increment of vacancy-like defects. It could decrease the coverage fraction of the defects by Cu atoms and annihilations with the Cu core electrons. The Cu content increasing in Fe-Cu alloys would enhance the coverage of the defects by copper atoms and increase the $\Delta W/W$ parameters.

Acknowledgements

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